The Study of Single Nb_3Sn Quadrupole Coils Using a Magnetic Mirror Structure

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Abstract— **Several 90-mm quadrupole coils made of 0.7-mm Nb_3Sn strand based on the "Restack Rod Process" (RRP) of 108/127 design, with cored and non-cored cables and different cable insulation, were fabricated and individually tested at Fermilab using a test structure designed to provide a quadrupole magnetic field environment. The coils were instrumented with voltage taps and strain gauges to study quench performance and mechanical properties. The Nb_3Sn strand and cable parameters, the coil fabrication details, the mirror model assembly procedure and test results at temperatures of 4.5 K and 1.9 K are reported and discussed.**

Index Terms— **Nb_3Sn quadrupole coil, magnetic mirror, critical current degradation, Nb_3Sn technologies scale up.**

I. INTRODUCTION

FERMILAB is involved in the development of a new generation of accelerator magnets based on Nb_3Sn superconductor with operating fields above 10 T and increased operating margins. The development and implementation of this new technology involves the fabrication and test of a series of magnet models, coils and other components with various design and processing features and structural materials.

A quadrupole magnetic mirror structure was developed at Fermilab to provide an efficient and fast way to test and optimize Nb_3Sn quadrupole coils. This structure allows us to test individual coils under operating conditions similar to that of a real magnet, thus reducing the turnaround time of coil fabrication and evaluation, as well as material and labor costs. Originally the "magnetic mirror" concept was developed for testing Nb_3Sn dipole coils at Fermilab [1, 2]. Long dipole mirror magnets were successfully used for the Nb_3Sn coil technology scale-up [3]. Implementation of the mirror configuration for a quadrupole magnet provides even greater benefits due to the larger number of coils in quadrupoles with respect to dipole magnets.

The quadrupole mirror models of the TQM series were used to study the effect of pre-stress on the Nb_3Sn coil performance, as well as to compare the quench performance of Nb_3Sn quadrupole coils with and without a stainless steel core in the cable. A 4-m long and 90-mm aperture quadrupole coil based on Nb_3Sn strand of the RRP 114/127 design with E-glass cable insulation has been fabricated and prepared for testing in a 4-m long version of the quadrupole mirror structure.

The details of coil fabrication and mirror model assembly, as well as the test results, are reported in this paper.

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II. TQM MODEL DESIGN AND TEST RESULTS

A. Coil Design and Fabrication Features

Technology quadrupole (TQ) coils with a 90-mm inner bore diameter are based on a 2-layer cos-2θ design with one wedge in the inner layer and a pole block in each layer. The TQ coil cross-section is shown in Fig.1. Details of the baseline TQ coil design and fabrication technology are described in [4, 5].

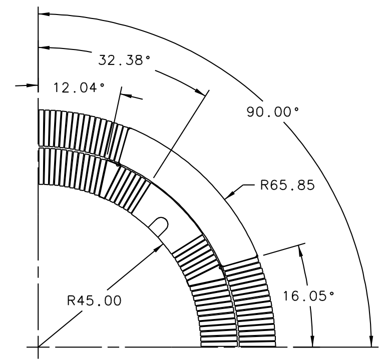

Fig. 1. TQ coil cross section

The specific features of coils used to study the effect of pre-stress (coil #34) and the effect of the stainless steel core in the cable (coil #35) are summarized in Table 1. Both coils were made of 27-strand Rutherford cable with 0.7-mm Nb_3Sn RRP strand of an advanced 108/127 design [6]. The cable for these coils was fabricated using Fermilab's cabling machine [7]. The cable in coil #34 was made without an interlayer core and insulated with an E-glass tape using standard cable insulating techniques. The cable in coil #35 has a 25-μm stainless steel (SS) core and was insulated with a S2-glass sleeve. The view of the cored cable used in coil #35 is shown in Fig. 2.

TABLE 1 COIL SPECIFIC FEATURES.

Coil #	Strand	Cable	Cable insulation	Ic (12T, 4.2K), A
#34	RRP-108/127	w/o core	E-glass tape	457
#35	RRP-108/127	SS core	S2-glass sleeve	416

Both coils were reacted using the same heat treatment cycle. The critical current values of witness strand samples for both coils are shown in Table 1.

Fig 2. SS cored cable used in coil #35

B. *Mirror Assembly and Coil Pre-stress*

The cross-section of the TQM quadrupole mirror model is shown in Fig. 3. Details of the mirror design and assembly procedure were previously reported in [8].

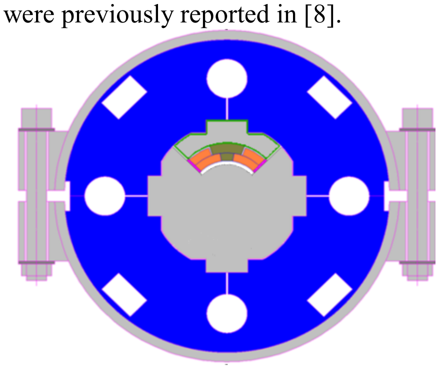

Fig. 3. Quadrupole mirror cross-sections with single 90-mm TQ coil

Coil #34 was assembled in a quadrupole mirror structure three times (TQM03a, TQM03b and TQM03c) with different coil pre-stress levels. The final level of coil pre-stress, i.e. cold pre-stress, was adjusted by the size of the vertical shims inserted between the mirror blocks and the upper yoke.

Coil #35 was assembled and tested in a quadrupole mirror structure (TQM04a) with the same warm and cold coil pre-stress levels as in the TQM03b mirror model.

The stresses of coils in TQM03b and TQM04a magnets were estimated using an ANSYS finite element model. Coil stress distribution diagrams at room temperature, after cooling down to 4.5 K, and at 4.5 K for a current of 14 kA are shown in Fig. 4. The maximum pre-stress in the coil inner-layer pole turns at room temperature and at 4.5 K is reported in Table 2. Room temperature stresses were derived from the coil strain gauges and at 4.5 K values were derived from the ANSYS model.

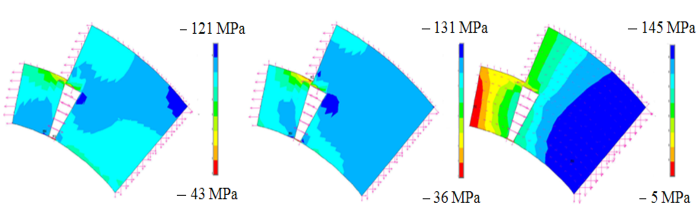

Fig. 4. Coil stress distribution in TQM03b and TQM04a mirror models at room temperature (left), at 4.5 K and 0 A of magnet current (center) and at 4.5 K and 14 kA (right)

The magnetic mirror models were tested in boiling liquid helium in the Vertical Magnet Test Facility (VMTF) at Fermilab. The test plan included quench training and ramp rate dependence studies at 4.5 K and 1.9 K, as well as temperature dependence studies.

TABLE 2 MAXIMUM INNER-LAYER COIL PRE-STRESS AT ROOM TEMPERATURE AND AFTER COOLING DOWN.

Mirror model	Coil pre-stress, MPa	
	300 K	4.5 K
TQM03a	95	80
TQM03b	105	130
TQM03c	135	185
TQM04a	105	130

C. *TQM03 Test Results*

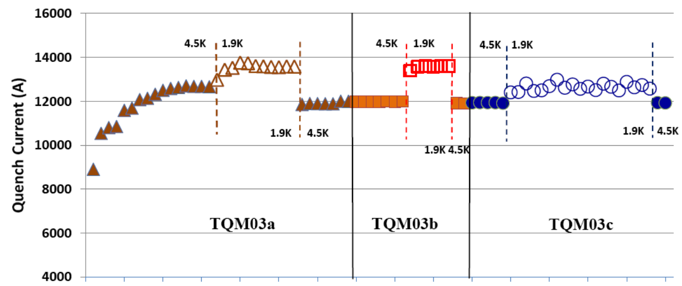

Fig. 5. TQM03 training at 4.5 K and 1.9 K

The training results of TQM03a, TQM03b and TQM03c both at 4.5 K and 1.9 K are shown in Fig. 5.

The first mirror assembly with coil #34 showed short training both at 4.5 K and 1.9 K. At 4.5 K, TQM03a reached a maximum quench current of 12.69 kA, which is 100% of its short sample limit (SSL) based on witness sample data. This coil, made of the new strand and insulation, showed the best training performance and the highest quench current.

Coil #34, made of RRP-108/127 Nb_3Sn strand showed good stability and an expected increase of quench current at 1.9 K. On its fourth quench, TQM03a reached a current of 13.75 kA or ~98% of its SSL at 1.9 K, but then the quench current decreased by ~200 A or to ~96% of SSL, possibly due to insufficient coil pre-stress.

The quench program was completed at 4.5 K by verifying the quench plateau. The magnet demonstrated ~ 6% reduction from the original quench plateau at 4.5 K due to (presumed) conductor degradation at 1.9 K.

After re-assembly with higher coil pre-stress TQM03b demonstrated good training memory and the same maximum quench currents both at 4.5 K and 1.9 K (see Fig. 5).

TQM03c, with the cold coil pre-stress at the level of 185 MPa demonstrated the same performance at 4.5 K but erratic quench behavior at 1.9 K. The fact that coil #34 exhibited erratic behavior only in TQM03c, assembled with the highest coil pre-stress, may indicate possible coil damage during the magnet assembly. Quenches at 1.9 K originate in the mid-plane blocks of the inner-layer coil. Plateau quenches at 4.5 K in all 3 TQM03 models were located in the outer coil (due to lack of the voltage taps we cannot locate more precisely quench origin in the outer coil).

Magnet ramp rate dependences at 4.5 K and 1.9 K are shown in Figure 6. Quenches at low ramp rates originated in the pole-turn blocks, while high ramp rate quenches were mostly located in the mid-plane blocks of both the inner and outer coils. One can see in Fig. 6 that eddy current induced losses and related reduction of the conductor margin at high ramp rates 300 A/s and 350 A/s are correlated with the coil pre-stress.

The residual resistivity ratio (RRR) of the conductor was measured in TQM03a and TQM03c. On average, RRR values changed from 190 in TQM03a to 175 in TQM03c.

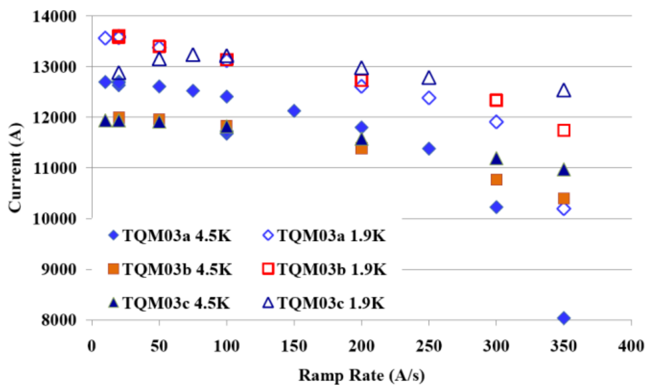

Fig. 6. TQM03 ramp rate dependences at 4.5 K and 1.9 K

The quench current dependence on magnet temperature was measured in the temperature range of 1.9-4.5 K and at a current ramp rate of 20 A/s. The results are presented in Fig. 7. TQM03a and TQM03b showed stable and reproducible quenches over the entire temperature range from 1.9 to 4.5 K whereas TQM03c showed the same performance only above 3.5 K. Most quenches below 3.5 K in TQM03c originated from the mid-plane blocks of the inner-layer coil. TQM03c performance at low temperatures is consistent with the magnetic instability previously observed in short dipole and long mirror dipole models [2, 9].

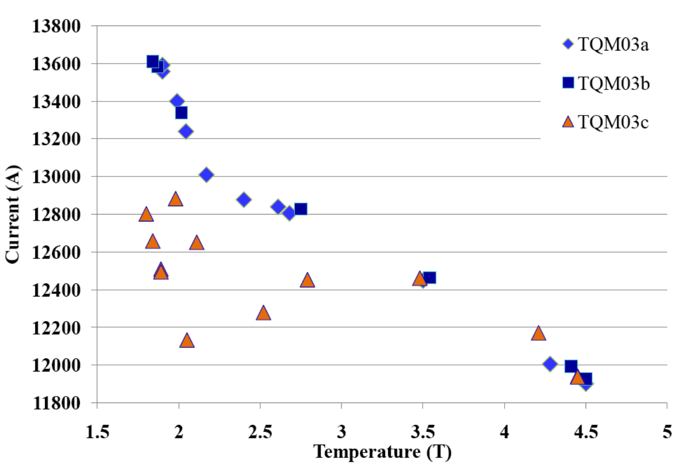

Fig. 7. TQM03 quench current vs. helium bath temperature at a ramp rate of 20A/s

Taking into account that coil #34 demonstrated stable performances in the first two tests, erratic quench performance at low temperatures in TQM03c can be attributed to the high coil pre-stress in this model. This pre-stress did not degrade the coil in the pole-turn blocks (high field region). Filaments in some strands could be damaged in the low field region of the magnet resulting in current redistribution and increased instability of conductor.

D. *TQM04a Test Results*

TQM04a was used coil #35 made of the same 0.7-mm Nb_3Sn strand of the RRP-108/127 design but with a stainless steel core in the cable (see Table I).

The training quenches of TQM04a both at 4.5 K and 1.9 K temperatures are shown in Fig. 8. For comparison TQM03a training quenches are also shown.

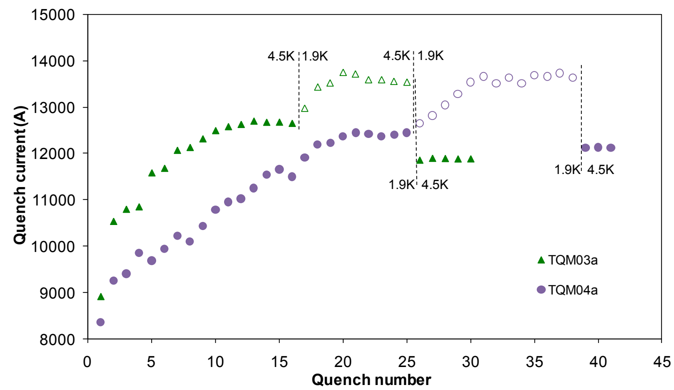

Fig. 8. TQM04a and TQM03a quench training at 4.5 K and 1.9 K

Training at 4.5 K started at essentially the same current level, but TQM04a reached a plateau after ~20 quenches while TQM03a reached plateau in only ~10 quenches. The longer training in TQM04a could be due to cored cable or/and higher coil pre-stress (see Table 2).

Quench training at 1.9 K is quite similar in both magnets. Some degradation observed in TQM03a after training at 1.9 K also was observed in TQM04a but at a smaller level, possibly due to the higher initial coil pre-stress. All plateau quenches in TQM04a both at 4.5 K and 1.9 K originated from the pole-turn blocks of the outer-layer coil, close to the return end.

The maximum quench current reached at 4.5 K was 12.5 kA or ~100% of the SSL, but after degradation at 1.9 K, the quench plateau was re-established at 12.2 kA or ~97% of the previous plateau. At 1.9 K the magnet reached 13.6 kA or ~97% of the SSL. The estimated SSL's for coil #35 are shown in Table 3.

TABLE 3 ESTIMATED SHORT SAMPLE LIMIT FOR COIL #35

	1.9 K	4.5 K
Coil #35 without self-field correction	13.88 kA	12.29 kA
Coil #35 with self-field correction	14.17 kA	12.53 kA

The TQM04a and TQM03a ramp rate dependences are compared in Fig. 10. The ramp rate dependence of TQM04a is quite different at high ramp rates at both 4.5 K and 1.9 K. The lower sensitivity to ramp rate for coil #35 is due to the lower inter-strand resistance controlled by the SS core.

The TQM04a test results confirm the efficiency of SS core in suppressing eddy currents in the cable which can cause deterioration of field quality in accelerator magnets during magnet ramping.

III. Long Coil Test in a Mirror Structure

A. Coil design and fabrication

The 4-m long coil has the same cross-section as the TQ coils described above with one exception. The coil leads were moved to other end of the magnet and mid-plane half-turns in the inner and outer layer were replaced with dummy pieces of Nb_3Sn cable.

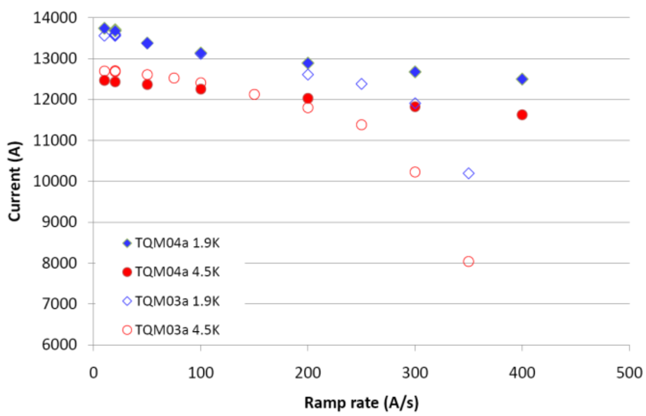

Fig. 10. TQM04a and TQM03a ramp rate dependence at 4.5 K and 1.9 K

The 27-strand Rutherford cable with 0.7-mm diameter RRP strand of 114/127 sub-element design in this coil was produced by Oxford Superconductor Technologies, Inc. [10]. The RRP strand of this design has a sub-element size of ~50 µm, a copper fraction of 49% and a twist pitch of 12 mm, providing a nominal J_c(4.2K, 12T) of ~2400 A/mm^2 with a matrix residual resistivity ratio (RRR) above 200 [11]. The ~200-m long cable unit with keystone cross-section was produced at Fermilab in one pass and annealed at 195^{o}C for 2 hrs before insulation. The cable insulation consisted of two layers: both layers were made with a butt lap of 75-µm thick E-glass tape.

Details of the long Nb_3Sn coil fabrication procedure are described in [12]. The 4-m long coil was wound from a single ~180-m long piece of cable without an inter-layer splice. The coil was cured after winding to a size ~0.5 mm smaller azimuthally to provide room for cable expansion during reaction to minimize mechanical stresses in the coil. The coil was reacted in a 3-step cycle with the last step at 646^{o}C for 51 hours; finally, it was impregnated with CTD 101K epoxy. A picture of the coil after reaction is shown in Fig. 11. The coil dimensions were measured in the free-state after impregnation to select appropriate pre-stress shims. Flexible NbTi leads were soldered to each of the inner and outer Nb_3Sn leads. Voltage taps were placed across each coil block to detect and localize quenches.

B. Long mirror assembly

The coil was assembled in a long quadrupole 'mirror' structure described above. Transverse preload to the coil was applied by a 12-mm thick welded stainless steel skin. Axial support was provided through end bolts attached to the end plates. The coil azimuthal stress was determined from capacitive and resistive strain gauge measurements. The coil axial preload was set using measurements from resistive strain gauges on the bolts.

The nominal maximum coil pre-stress was ~100 MPa at room temperature and ~145 MPa after cool down similar to TQM03b and TQM04a.

Fig. 11. 4-m long Nb_3Sn quadrupole coil.

IV. Conclusion

The effect of stresses up to 185 MPa on the quench performance of TQ coils made of Nb_3Sn RRP-108/127 strand has been studied using a single quadrupole coil in a magnetic mirror configuration. No measurable degradation was observed at temperatures above 3.5 K. Erratic quench performance, consistent with magnetic instability, were observed at temperatures below 3 K with a coil pre-stress of ~185 MPa. Complementary results were obtained during the tests of LARP quadrupole model TQS03 made of the same RRP-108/127 strand [13].

A Nb_3Sn quadrupole coil with a SS core in the cable was tested in a magnetic mirror structure. Test results confirmed the efficiency of the SS core in suppressing eddy currents in the cable without significant impact on coil training.

The first 4-m long shell-type Nb_3Sn coil made of 0.7-mm RRP strand with a 114/127 sub-element design was fabricated and prepared for testing in a long quadrupole mirror structure. This work complements the Nb_3Sn technology scale up program for LARP in preparation for 4-m long large-aperture Nb_3Sn quadrupoles of LQ series [14].

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